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ROY L. LOVVORN, Administrator

Where the Action Is

Today's emphasis on man and the environment places science at the center of some of the most urgent problems of modern times. People abound who contend that science deserves this difficult posision since, they say, science itself is responsible for most of these woes. A sound case can be made against such allegations by pointing out very real differences between science and technology. This can be morally comforting, yet the fact remains that technology, which is not science but is a product of it, uses scientific findings in developing its wares, many of which have led to the exploitation and degradation of our natural resources.

Rich as we are in research findings that can help solve our technologically-created problems, science must continue to help us better understand the highly complex relationships within the natural and manmade world and, so very important, the behavior of man within it.

Many of those who are disillusioned by science claim it has failed to attack where it should: at the people level. To help offset this, more research in the social sciences is needed. At the same time, research in other areas cannot be neglected. Thus, the problem of balance is central.

Scientists and administrators of science programs are becoming increasingly aware of these concerns and challenges. You will find indications of this in the articles in this issue of the *Review*.

Then comes the toughest task of all, which involves us all—scientists and non-scientists alike: somehow see that the technology generated by research will be applied in such a way as to make the wisest possible use of our natural, including human, resources.—J.W.W.

Complementary Aspects of Phytotron and Field Facilities in Environmental Physiology Research

R. J. BULA

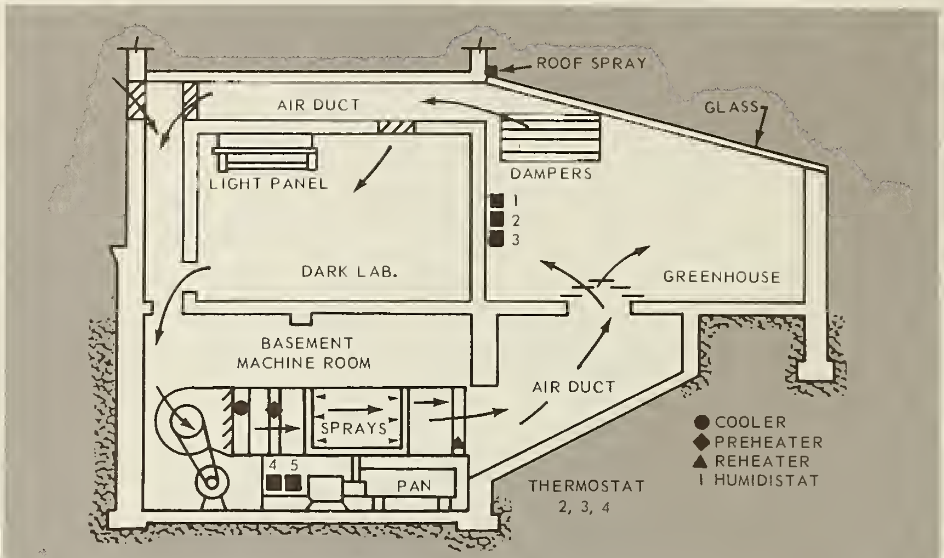
YIELD, in terms of quantity and quality of the product, is the most important consideration in crop production. Consequently, the practical objectives in agronomic research are to determine what factors of the plant or its environment are limiting the production of useful dry matter, and to develop procedures (such as new varieties, pest control programs, or fertility practices) that will adjust the limiting factors and thereby ensure maximum crop productivity.

Weather and Crop Yields

IT is tempting to conclude that since plant material is the product of photosynthesis, the analysis of yield can be reduced to a study of the photosynthetic systems of a plant. This is an obvious oversimplification because accumulation of photosynthates as useful dry matter involves many other physiological processes both directly and indirectly (*10*).

Likewise, we know that weather factors such as temperature, humidity, and daylength have an overriding impact on many metabolic processes that in turn affect growth and yield. The greatest fluctuation in yield from year to year can be accounted for by differences in weather conditions (*18*). With such crops as corn and soybeans, highest yields have been obtained in those years when June temperatures were warmer than normal but July and August temperatures were cooler than normal. These

Italic numbers in parentheses refer to Literature Cited, p. 6.



Diagramatic Arrangement of the California Phytotron

weather conditions favor rapid germination and seedling development during the early part of the growing season but reduce temperature and moisture stress during that part of the growing season when the grain yields are accumulating.

Historical Development of Phytotrons

THE influence of weather on crop yields was initially studied through the use of regression techniques relating weather and yield. Although these studies have revealed some interesting relationships, many questions remain concerning the manner in which environmental control of crop yields is exercised. An alternative approach was the development and use of controlled environment facilities.

The success of the Earhart Plant Research Laboratory, built in 1948 at the California Institute of Technology (*20*), provided the stimulus for the development of phytotrons or installation of controlled environment facilities at essentially all major plant science research centers. During the late 1950's and 1960's, a number of phytotrons were constructed throughout the world. Among these are the phytotron of the State Institutes, Wageningen, Netherlands, in 1958 (*1*) ; the CERES phytotron of CSIRO in Canberra, Australia, in 1962 (*16*) ; the phytotron of C. N. R. S. at Gif-sur-Yvette, France; the phytotron of the Hokkaido National Agricultural Experiment Station in Sapporo, Japan, in 1966 (*23*) ; the biotron at Kyushu University in Fukuoka, Japan, in 1966 (*15*) ; the biotron at the University of Wisconsin in 1966, the Southeastern Plant Environment Laboratories (SEPEL) at Duke University and North Carolina State University in 1968 (*13*) ; and the New Zealand Climate Laboratory of DSIR in Palmerston North, New Zealand. These major facilities, although intended primarily for use by their staffs, are generally available to qualified investigators whose research objectives are consistent with the basic capability of a phytotron—that is, to provide an opportunity to study plant response over a wide range of environmental conditions.

Concurrent with the construction of these phytotrons, smaller-scale controlled environment facilities were developed at numerous research stations. Many of these installations could be technically classified as phytotrons but generally are not, simply because they lack the number of rooms and the implied nucleus of staff associated with a phytotron.

With the widespread availability of controlled environment facilities, the question arises, from an administrative and a research standpoint, whether research on the environmental physiology of crop species could more logically be conducted in phytotrons rather than under field conditions. The compelling argument is that the phytotron provides

reproducible environmental conditions, thereby permitting an independent analyses of how each environmental factor is involved in the control of plant growth and development.

Field Environments Fluctuate Continuously

MANY agronomists are skeptical of controlled environment data because maintenance of all environmental conditions at constant levels except those under evaluation exposes the plant to an environment vastly different from that in the field. In fact, most, if not all, plants require a fluctuation of environmental conditions in order to proceed through their normal development. Also, as has been pointed out by Evans (*9*), plants under field conditions develop as a community. This results in marked interactions among the plants; under controlled conditions, plants are not exposed to such conditions.

A comprehensive description of the micrometeorological conditions of crop canopies is essential for environmental physiology research in the field as well as to provide a basis for establishing environmental conditions for research conducted in a phytotron. Such a description should include a characterization not only of the highly dynamic conditions but also the interrelationships of the environmental changes.

The effects of radiation on CO_2 concentration as a result of photosynthetic activity are obvious; often overlooked, however, are the effects of radiant heating of the air on CO_2 diffusivity as pointed out by Duncan and Barfield (*8*).

Superimposed on these short-term dynamic changes are the seasonal weather patterns. In the temperate and polar regions, these weather changes are of sizable magnitude. Such changes may be regular and predictable, such as daylength, or subject to fluctuations within a general range, such as temperature and sunlight. Many of the seasonal environmental changes are closely related, as in the case of the micrometeorological conditions.

Time and Space Considerations in the Field

SINCE the environmental variables in the field are rarely independent, interpretation and analysis of their effects on plants are difficult. Repeating a field experiment at different times or areas does not necessarily provide a range of environmental conditions, as often assumed. The lack of success with regression techniques to relate various environmental variables with yield can invariably be traced to the inherent correlation between environmental variables. For example, plant response should be measured under cool, dry, low radiation conditions as well as under hot, dry, low radiation; cool, wet low radiation; hot, wet, low radiation; cool, dry, high radiation, etc., conditions. To obtain such environmental and plant data is a much greater task than most environmental scientists realize. It involves judicious planning, availability of instrumentation and land area, and probably most importantly, the fortuitous possibility that the appropriate weather conditions will develop.

A further complication involved in field studies is that plant development progresses through a seasonal pattern. This is important because the effects of weather exposure may vary, depending on stages of development, such as the seedling stage, vegetative growth, flowering, or grain development. Extrapolation of either the weather or plant data from short-term observations to seasonal trends is difficult because invariably biological processes are not linearly related to the weather factors.

The preceding comments emphasize the complexity of doing environmental physiology research under field conditions and were not meant to imply that it is impossible to do such research in the field. On the other hand, the phytotron may not reproduce the dynamics of a natural environment, but such facilities do provide us with an opportunity to vary the environmental factors independently and thus segment the research to the extent that reasonable interpretations of plant response can be made. In this context, it is essential that we understand the differences between the simulated environments of a phytotron and the natural environments of the field.

PHYTOTRONS IN AGRONOMIC RESEARCH

Photoperiodic Responses of Crop Species

MANY reports in the literature have pointed to the effectiveness of phytotron environments in separating the effects of environmental factors that are closely related in the field. Studies dealing with the photoperiodic responses of soybeans, corn, tobacco, red clover, and wheat are examples of such research.

A basis for the north-south adaption of soybean varieties was provided by the photoperiodic studies of Borthwick and Parker (*4*). Blyth (*3*) described differences among temperate and tropical soybeans in rate of floral initiation and plant development and suggested that such information could be useful in predicting areas of adaptation of this species.

Likewise, flowering of exotic races of corn has been studied so as to obtain more information on the controlling mechanisms of vegetative and floral development in this species (*17*). A better understanding of the photoperiodic responses of these diverse races would facilitate their use in breeding programs because these races are a source of many desirable traits. Blair and Patterson (*2*) studied the ability of winter wheat varieties to head when grown under controlled conditions and suggested the use of this information to predict potential adaptation of new lines in wheat breeding programs. Kasperbauer (*12*) has shown that floral induction and development of tobacco was enhanced by an interaction of the effects of cool temperatures and short photoperiods. Floral development of a red clover ecotype was shown to be stimulated by low temperature exposure if the plants are subsequently grown under long photoperiods (*5*). In another ecotype, flowering occurred under long photoperiods but without the requirement for low temperature exposure.

These and similar studies have demonstrated that floral response of many crop species is controlled by the interaction of photoperiod and temperature conditions. Controlled environment facilities provide the most feasible means for studying the role of these environmental variables in regulating flowering of crop species. Field observations of flowering response, however, provide an excellent complementation to the phototron studies in developing our understanding of flowering physiology of crop species.

Partitioning of Photosynthates

PARTITIONING of the photosynthate to various plant organs and growth functions is an important phenomenon that needs to be considered in assessing the efficiency of any crop. Maximum yields would be realized if the photosynthates were partitioned into development of those plant parts that constitute harvestable yield. In young developing seedlings, photosynthate is partitioned primarily between growth of leaves (expansion of photosynthetic surface) and the root system. As the plant develops, other sinks are formed that compete for the available energy. These sinks may represent the harvestable yield, as ears do in corn, or may not be an important part of yield, i.e., floral development in forage crops or sugar beets.

Many perennial species exhibit a marked tendency for accumulating photosynthates in storage organs during the autumn period. Under the fall conditions of shortening photoperiods and cool temperatures, photosynthate is partitioned to accumulation of carbohydrates in storage organs in preference to expansion of photosynthetic area. However, under spring or summer conditions, long photoperiods, and warm or hot temperatures, leaf expansion and flowering are able to attract the photosynthate in preference to accumulation in the storage organs.

Plant hormones may play a significant role in regulating the partitioning of photosynthates. A cybernetic model of growth relationships among various plant organs has been proposed based primarily on the hormonal characteristics of the organs involved (*11*). How the effects of these hormones on plant growth are modified by environment would be a useful addition to such a model and make it more meaningful to crop physiologists.

A more definitive description is needed of how environment interacts with hormones in regulating the distribution of photosynthates among leaves, stems, roots, storage organs, or seeds. To accomplish this will require the cooperative efforts of those working in the area of plant hormone physiology and environmental physiology. Again, field studies can provide significant and complementary information to that derived from phytotron studies.

Plant Morphogenesis and Development

ANOTHER significant response is that involving interactions of environment and plant morphogenesis. A number of examples of how plant form and shape can be modified by weather conditions have been described by Went and Sheps (*21*). Vegetatively propagated plant material established at various geographic sites invariably shows marked alterations in size, shape, and development.

An agricultural engineer at USDA's Light and Plant Growth Laboratory, Beltsville, Md., compares the growth of lettuce plants—the smaller one grown under greenhouse conditions, the larger in a specially designed growth chamber.

These observations are significant to crop productivity in view of recent reports that some morphological characteristics of leaves may be related to their photosynthetic capability (*7, 22*). A positive relationship between leaf weight per unit area and net photosynthetic rates of several forage species has been reported by Carlson *et al* (*7*). Anatomical features of leaves as affected by environment may have a profound influence on CO_2 diffusion from the stomatal cavity to the pallisade cells and from the surface of the pallisade cell to the chloroplast. Equally important may be the volume of vascular tissue to facilitate translocation of water to the leaf cells and photosynthate away from the pallisade cells (*6*).

Studies of the effects of environment on plant morphogenesis have been conducted effectively under field conditions. Additional research conducted in phytotron facilities will favorably complement the field studies and provide the basis for describing the quantitative relationships of environmental factors with morphogenesis and developmental physiology.

Development of Simulation Models

THE studies cited in the previous sections provide examples of how phytotron facilities can effectively contribute toward crop physiology research. However, the great potential of using phytotron facilities to complement field studies in the new and rapidly developing field of simulation modeling for predicting crop productivity is just beginning to be realized.

Our knowledge of the qualitative and quantitative relationships of environment and many basic plant processes, such as photosynthesis, dark and light respiration, translocation, or cellular growth, is inadequate for a direct approach to development of

such models. The validity of many aspects or components of these models needs to be experimentally evaluated and verified. As Waggoner (*19*) points out, an important contribution of the simulation model approach is that it identifies the physiological processes most related to the aspect of plant growth being modeled as well as pointing out where the gaps of knowledge exist. Lomis (*14*) emphasized that modeling and experimentation are interdependent and that the experimentation needs to be done both in phytotron and in the field.

Hopefully, in the foreseeable future, crop physiologists will be able to describe plant response to environmental conditions and meterologists will be able to describe the physical environment of a crop. Availability of accurate long-range weather forecasts can then be coupled with predictive plant response models to provide highly tailored information on which to base crop management decisions and thereby increase the efficiency of crop production.

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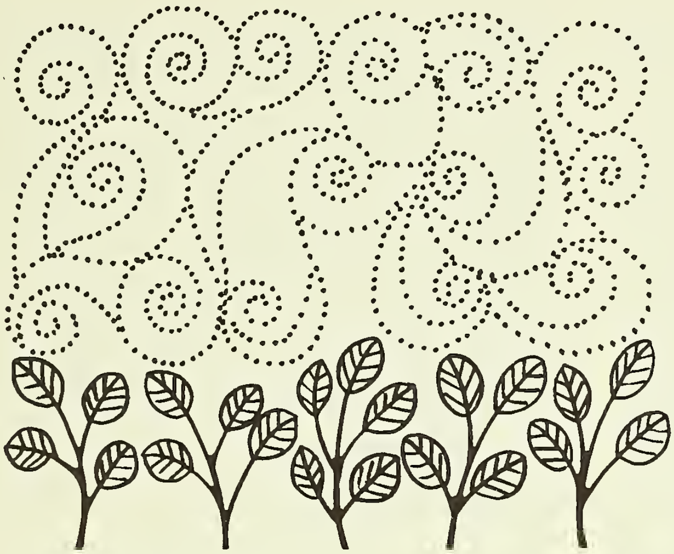

ANALYZING ATMOSPHERIC TURBULENCE IN PLANT CANOPIES

R. D. BRAZEE and R. D. FOX

ALTHOUGH urban environmental concerns are more widely publicized than those in rural areas, the pollution problems that can arise in our croplands have long been recognized by agriculturists. In some cases, atmospheric pollutants have caused severe crop damage. Particularly serious effects have been found near industrial centers and heavily traveled expressways. Some agricultural practices, however, create pollution themselves, such as when odors from disposed wastes or drift from chemical spraying operations get into areas where they are objectionable. Most pesticide application methods make it especially difficult to avoid some pesticidal drift into areas where it may create danger. Pesticide application research, however, is attempting to minimize chemical drift, and alternative pest and disease control measures, including biological methods, are also under development. Many of the new techniques, as well as chemical application, are affected to some extent by the atmosphere within and near the plant canopy. Consequently there is much interest in plant-canopy micrometeorology.

Air pollution and pest control problems are not the only causes for interest in plant micrometeorology. The atmosphere's role in plant growth and nutrition is being studied more intensively than ever before (*6, 26, 34, 38, 49*).[1] Scientists trying to computer-simulate plant functions and growth processes need information about the plant-canopy atmosphere for input to their mathematical models. Lemon *et al.* (*26*) regard the need for a better understanding of plant canopy fluid dynamics as a limiting factor in present plant models. Soil conditions are also affected by the heat and gaseous exchange processes occurring in the adjoining atmosphere. There have been efforts to promote faster growth and earlier maturity by enriching the plant atmosphere with carbon dioxide (*2, 24, 25, 34*).

The processes involved in pollutant transport, pesticide drift, and plant growth environment are clearly similar. The atmospheric transport mechanisms are much alike whether the material is a pollutant, a pesticide, or a substance exchanged with the plant in its life processes. Heat, gases, water vapor, aerosol particles and droplets, and plant pathogen spores are all effectively dispersed by wind convection and turbulence. Differences in the way properties are transported depend on whether they occur at the molecular level, such as heat, or as a

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[1] Italic numbers in parentheses refer to Literature Cited, p. 21.

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gaseous admixture, or as discrete liquid or solid particles. This factor determines the degree to which the movement of transported material is coupled to ambient air motion.

The principal transport effects in a plant-canopy atmosphere are convection, turbulent dispersion, and molecular diffusion. *Convection* is the transport of substance from place to place by wind. *Turbulent dispersion* causes large-scale spreading of a transported substance, as it is convected, an example being a broadening smoke plume. *Molecular diffusion* occurs in conjunction with turbulent dispersion, but is a small-scale dispersive effect. Turbulent dispersion is usually the predominant of the two effects, and is also the lesser understood. Thermal transport effects are active for small particles very close to leaves or stems. An example is *thermophoresis,* a molecular kinetic phenomenon whereby small particles may be driven away from a surface which is warmer than the ambient air temperature.

Understanding transport processes in the crop canopy requires knowledge about the complex atmospheric boundary layer which penetrates the vegetation. Within the boundary layer, wind velocity decreases from its rate in the free flow above the layer to zero at the soil surface. This velocity gradient creates a shear flow condition which is a strong factor in generating turbulence.

The physical sciences and engineering have accumulated a vast literature on boundary-layer flow parallel to smooth walls. Smooth-wall flow theory is helpful in visualizing boundary-layer structure, even though it may be a crude approximation to that of the atmosphere. Immediately adjacent to the wall is a region called the *viscous sublayer,* where flow is dominated by viscosity effects. Outside the viscous sublayer is the *intermediate* or *transition region* where flow is neither completely viscous nor turbulent. Beyond the transition region, the flow becomes completely turbulent. The boundary layer velocity profile close to the wall is affected by the *wall roughness,* particularly if the average height of protuberances, or *roughness elements,* is greater than smooth-wall viscous-sublayer thickness. For this reason fluid dynamicists distinguish between smooth- and rough-wall boundary layers.

In boundary layers encountered in most aircraft or engineering work, roughness-element heights are only a few millimeters at most, and typically are only fractions of a millimeter. In contrast, the atmospheric layer in which disturbed shear flow occurs is much thicker. In the *atmospheric surface layer,* extending from the ground up to 50 to 100 meters, the wind structure is determined by surface details and the vertical temperature gradient. The *planetary boundary layer,* which includes the surface layer, extends to about 500 to 1,000 meters elevation. The region between the upper limits of the surface and planetary layers is a transition region wherein wind structure is influenced by surface friction, density gradient, and the earth's rotation. Beyond the planetary layer is the free atmosphere, where the *geostrophic wind* is attained and viscous effects become small.

A growing crop adds a canopy-flow layer which may be from a few centimeters up to 2 or 3 meters thick. The crop constitutes a roughness element which generally prevents formation of a viscous sublayer. Thus, the canopy has an *aerodynamically rough* configuration and air motion is turbulent down to the soil surface. The canopy also influences the flow above it as would any other roughness element. Therefore, in canopy micrometeorology it is necessary to study a turbulent system which extends from above the canopy to the soil surface.

Little is known about the details of turbulent transport processes in even the simplest of shear flows. No comprehensive theories are available and few definitive experiments have been done. Yet, the plant canopy flow represents a complex form of such a system. The canopy system also abounds in other complicating factors and their interactions. Radiation, aerosols, various gases, and water vapor exemplify factors which must be considered.

While a number of significant factors in the plant microclimate require study, this discussion will be limited to the atmospheric turbulence aspects. Some of the fundamental physics of turbulence and turbulent transport will be outlined along with measurement methods and mathematical concepts currently used in analyzing turbulence.

ATMOSPHERIC SYSTEMS

THE atmosphere may be studied on various scales—all the way from its global structure to the microclimate around plants or animals. Some standard terms help define the size of the atmospheric subsystem being investigated. For example, the atmospheric subsystem encompassing an entire con-

tinent is called a *macrosystem.* A system bounded by a statewide or local area is usually referred to as a *mesoscale* system. Over the past few years the terms *microscale,* or *micrometeorology,* have been commonly used. These terms denote a system which may include a region up to a few hundred meters in height and covering several square kilometers at most. On a still smaller scale, an *ectoscale* system may include only a single plant or leaf and its adjacent atmosphere.

So far, even the smallest scale systems resist complete definition. Larger systems, containing many subsystems, are still more complex. Generally, a meteorological system's behavior is predicted for only a short time in advance on the basis of prior observations. This is basically today's procedure for daily weather forecasting.

Despite its complexities, the atmosphere possesses regularities; the daily and seasonal variations in solar radiation, wind velocity, and temperature are typical. Also, large atmospheric systems tend to persist and give short term regularity to weather as they move across a region.

The atmosphere's motion depends on its energy budget, flow properties, and boundaries. Its major energy source is solar radiation, from which the upper atmosphere absorbs shortwave radiation and allows longer wave-length radiation to reach the earth's surface and keep it at fairly uniform temperature. The atmosphere redistributes heat over the earth, reducing the temperature gradients created by uneven heating of various regions.

Strong convective processes underlie the turbulent flow and transport mechanisms of the atmosphere. *Free convection* due to thermal buoyance effects, and *forced convection* due to flow and viscous effects at the soil interface, are both active. The two processes are essentially independent in the transport of heat. Free convection and the large-scale turbulence associated with it are very efficient mechanisms of heat transport. Forced convection and its accompanying smaller-scale turbulence are much less effective in transport. Also, forced convective transport is usually restricted to regions near the ground.

The laws of thermodynamics and fluid mechanics must be the starting point for any attempt to model an atmospheric subsystem. Fluid motion is representable by a well-developed set of differential equations. Unfortunately, these equations are highly nonlinear and have never been completely solved except for simple conditions such as laminar flow. *Laminar flow* is a state of regular streamline flow without the irregular, tumultuous motion of turbulence. Knowledge of laminar flow is well developed, since relationships among pressure, temperature, and flow velocity can be studied with less difficulty.

THE NATURE OF TURBULENCE

TURBULENT flow, a state of highly irregular fluid motion, is not completely understood; yet it is a more common condition than laminar flow. Turbulence defies many of the familiar analytical and experimental methods for studying flow, and requires new concepts and methods of measurement and analysis.

In 1937, Taylor and von Karman (*47*) defined turbulence as "an irregular motion which in general makes its appearance in fluids, gaseous or liquid, when they flow past solid surfaces or even when neighboring streams of the same fluid flow past or over one another." This irregularity is an important characteristic of turbulence. Flow velocity, for example, is nondeterministic in the sense that it can't be exactly predicted from its past history. Fortunately, the irregularities of turbulence are such that it is possible to describe it with the aid of probability methods. Distinct average values of density temperature, pressure, and velocity are obtainable. If turbulence were entirely chaotic, with no *statistical* regularity, it would be inaccessible to any useful conceptual or analytical treatment. Consequently, the philosophy of the statistical approach is that one neither knows nor needs to know all details of a turbulent flow field. Quantities such as velocity are regarded as random variables and handled accordingly. Since it is possible to deal with turbulence in this way, it is not adequate to simply define turbulence as irregular fluid motion. A more precise modern definition is that, "turbulent fluid motion is an irregular condition of flow in which the various parameters, such as velocity, show random variation with time and throughout space such that statistically distinct average values can be discerned (21)."

There are important features of turbulence which are not apparent in the above definitions. Lumley and Panofsky (*28*) list several properties of turbulence which must be recognized: (1) Turbulence is

rotational and *dissipative,* so that its energy of motion is degraded to internal energy of the fluid through a cascade of eddies of continuously diminishing size. Turbulence is (2) *three-dimensional* and (3) *nonlinear,* since this energy transfer takes place by a process called vortex stretching which is known to be three-dimensional and nonlinear. Turbulence is (4) *random,* or *stochastic,* for no matter how carefully an experiment is replicated, the turbulent flow state is not predictable in detail. Turbulence is (5) *diffusive,* for a tracer particle in a turbulent fluid will wander about, traveling ever farther from its initial location. The (6) *time and length scales* of turbulent motion are generally large, often being of the same order as time and length scales for properties or substances being transported. Finally, (7) turbulence can be regarded as a *continuum phenomenon,* since the average dimensions of flow phenomena are much larger than intermolecular or molecular distances inherent to the fluid.

The definitions imply that not all irregular fluid motion is turbulent, for random three-dimensional motions are possible which are approximately irrotational and nondissipative. Examples are a body of water subject to surface disturbance by a turbulent wind, or fluid flow outside a turbulent boundary layer. For flows to be classed as turbulent, they must dissipate mechanical energy to internal energy of the fluid by a cascade of eddies of diminishing size. Atmospheric motion nearly always meets these important criteria and is turbulent.

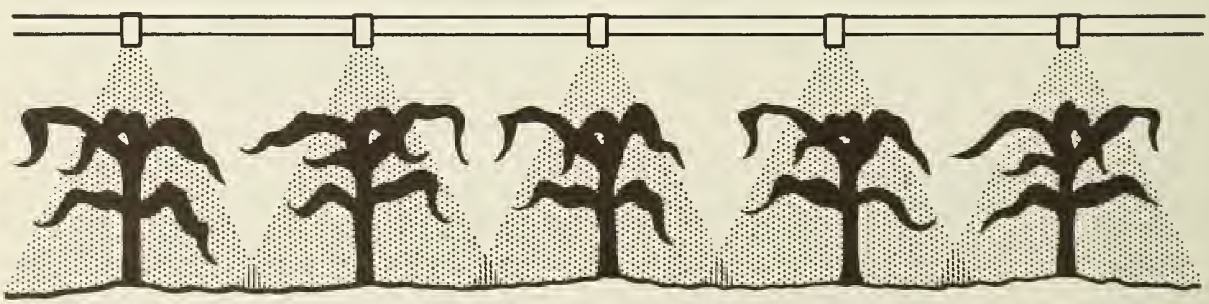
Some qualitative features of turbulence have now been outlined, but a more quantitative understanding of turbulence processes is needed. For one to advance beyond a purely empirical understanding, methods must be found for analyzing the complexities of turbulence.

TURBULENCE ANALYSIS

A plot of turbulent velocity against time exhibits the very irregular and seemingly unpredictable behavior typical of turbulence. While limited qualitative study and rough estimates of velocity magnitude are possible with such a record, special techniques are necessary to uncover important physical information masked by its irregularity. Analyses proceed in ways similar to those used by statisticians in handling random data and, in fact, probability methods are further used to model turbulence dynamics.

Statistical turbulence theory originated with G. I. Haylor's pioneering work in 1935 and later (*42, 43, 44*). Except for an earlier paper by Taylor (*41*), there was no recognition prior to 1935 that turbulent motion is a continuous random variable in position and time. Previous theories were based on analogies with the discrete-molecular-collision concepts used in the kinetic theory of gases.

In statistical analysis, means, variances, and higher-order population moments are estimated from sample statistics. The population moments represent ensemble or probability averages for a system. Similarly, turbulence as a physical system is expected to have quantitative statistical properties with associated probability averages. In turbulence analysis, these probability averages are again represented by sample averages. However, turbulence sample averages are generally different in that they are determined by averaging the corresponding random variable over some *region of space* or *interval of time.* These averages, called *space* or *time averages,* are very important experimentally, since the corresponding probability averages may be impractical to obtain.



It is important to recognize that time and space averages in turbulence are assumed equivalent to their corresponding probability averages. This *ergodic* assumption has not been rigorously established by either analysis or experiment. A system is called ergodic if time or space averages of any random variable in a single system are the same as the probability average obtained from observing many similar systems simultaneously. For turbulence, it would hardly be possible to proceed experimentally without the ergodic assumption. It means that instead of having to observe a very large number of systems all at once, one can obtain turbulence statistics by watching a single system for a period of time or over an interval in space.

In the remaining discussion, the time average will generally be implied for convenience.

The Statistics

To adequately describe a turbulent field statistically, velocity and other data may be required at several positions for some period of time. The numbers of points and sampling durations can be set with the help of familiar statistical goodness-of-fit and variability tests. The experimenter must also exercise judgment based on experience, knowledge of turbulence and the configuration of the system. An important working rule for time averaging is that the sampling duration must be long enough to reliably sample fluctuations of the variable under study, but not so long that slow trends will appreciably affect the results.

Since turbulence structure may vary over both time and space, the joint variation of a number of random variables may need to be studied. In statistics, this implies that a *multidimensional statistical distribution* is needed. In fact, if such a distribution were found it could, depending on its degree of generality, completely describe the turbulent fluid motion. Unfortunately, such a distribution might embody so many variates that it would be impractical to obtain.

As a result of these difficulties, investigators usually employ some alternative. Statistical parameters are used which can be related to the generalized distributions but are simpler to obtain. These quantities include means, variances, correlations, or higher-order moments which are convenient to measure and permit physical interpretation in themselves. In many studies, this course is followed when the general distribution is not known or even desired.

The Mean

For turbulence, the mean represents the average flow velocity observed at some location over a time interval T. If an ordered sequence of N discrete velocity measurements are recorded at uniform time intervals of length Δt, the averaging time is

$$T = N \cdot \Delta t.$$

Then if the instantaneous flow velocity component is denoted by U_i, the average velocity, $\bar{U}$, is simply

$$\bar{U} = (1/N) \cdot \sum_{i=1}^{N} U_i.$$

The mean velocity $\bar{U}$ is often unique to a specific observation location, and may be different at another position. For example, a vertical profile of mean velocity in a crop canopy exhibits nearly a continuous decrease in $\bar{U}$, from the open flow above the canopy down to zero at the ground.

Mean velocity indicates the average mass movement past the observation point per unit time. Atmospheric *advection* (horizontal transport) or *convection* (vertical transport) can be estimated with the aid of the mean. The mean velocity usually is stated either as components in three mutually perpendicular reference directions or else as the direction and magnitude of the total average velocity.

In steady uniform-flow, as in a wind tunnel, it is relatively simple to map mean flow. In the atmosphere, however, the wind is continually changing direction and speed. Thus, an atmospheric mean velocity must be qualified as to when and for how long the sample was taken, since the averaging time can decidedly influence the result.

Turbulent Velocity

The total instantaneous and mean velocities, U and $\bar{U}$, have been introduced, but the *turbulent velocity* remains to be defined. The turbulent velocity, u, is additively superimposed upon the mean velocity, so that the total instantaneous fluid velocity is

$$U = \bar{U} + u\ .$$

This relationship automatically requires the average

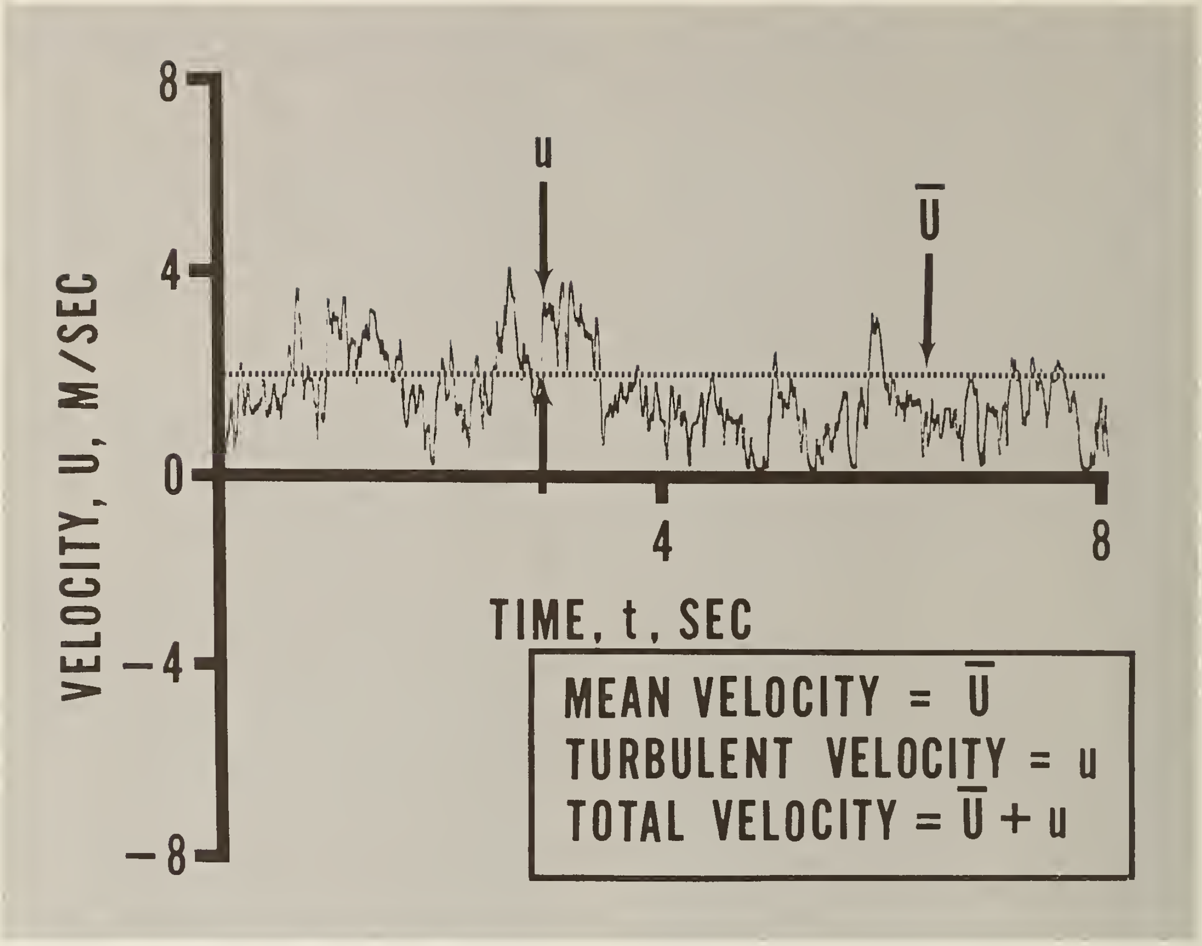


Fig. 1.—Velocity partitioning in turbulence analysis. The velocity record shown was obtained with a hot-film sensor at 0.93 meter above the ground in a corn canopy of about 1.6 meters in height.

of the turbulent velocity u to be zero. This ideally partitions the instantaneous velocity U into components as in the velocity sample of figure 1. However, partitioning may not be as simple as it appears because of the difficulties in defining a mean in atmospheric turbulent flow.

A map or profile of mean flow in a crop canopy indicates how a substance would be convected or *displaced* from one location to another. Accompanying this displacement is *dispersion* due to the action of turbulence; the random nature of the turbulent velocity u is an essential cause of this dispersive effect. Therefore, statistical characteristics of the turbulent velocity are sought as measures of dispersion.

Velocity Standard Deviation

SINCE the turbulent velocity u has been defined to have a mean of zero, the obvious next step in its characterization is to consider the standard deviation or, alternatively, the variance. The velocity standard deviation u', or variance $(u')^2$, measures the spreading of the turbulent velocity magnitude, showing the extent of its variation about the mean velocity. The velocity variance is computed by the familiar method

$$(u')^2=(1/N)\sum_{i=1}^{N}(U_i-\bar{U})^2=(1/N)\sum_{i=1}^{N}u_i^2,$$

wherein a sequence of velocity observations is used

as for the mean.

The standard deviation and variance of the turbulent velocity are often called the root-mean-square (RMS) and mean-square (MS) velocities. Physically, a MS-velocity measures the total turbulent energy associated with its velocity component. The RMS and mean velocities together provide an estimate of *turbulent intensity,* I, which is defined as

$$I = u'/\overline{U}.$$

In carefully designed wind tunnels, turbulent intensity is generally less than one percent. In comparison, atmospheric turbulent intensity is rarely less than 10 or 20 percent and is usually much higher. Turbulent intensity estimates are very important when selecting techniques for obtaining experimental data on a turbulent flow. Relatively simple measurements may be adequate for flows of less than 10 percent intensity. In high-intensity turbulence, however, these measuring methods fail and corrections, three-dimensional measurements, or other special procedures are required.

Being a measure of dispersion in statistics, the RMS- or MS-velocity similarly indicates the dispersive effect of turbulence. Modern turbulent dispersion theories use dispersion or diffusion coefficients which contain the RMS- or MS-velocity as a critical parameter.

The MS-velocity is a *second-order moment* which can be computed for any one of the three velocity components. It is also generalized as a *covariance* when computed for any two of the three components. In the latter case, the two velocities may be at either the same or different observation stations.

In some investigations, third or higher order moments are obtained, since they may carry important additional information about a turbulent flow, particularly when it is nonuniform. In such cases the mean and variance alone do not adequately define a turbulent flow, but the mean, variance, and all moments up to some higher order can uniquely determine the statistical distribution of turbulent velocity. The degree to which this goal is pursued depends upon the fortitude of the investigator. Alternatively, some workers try to gain insight into the nature of velocity distributions by obtaining the *single-component probability density* (*velocity histogram*).

Probability Density

THE velocity probability density shows, as a function of velocity, the proportion of the time that the turbulent velocity spends near any given level. To illustrate, a short segment of a recording of total

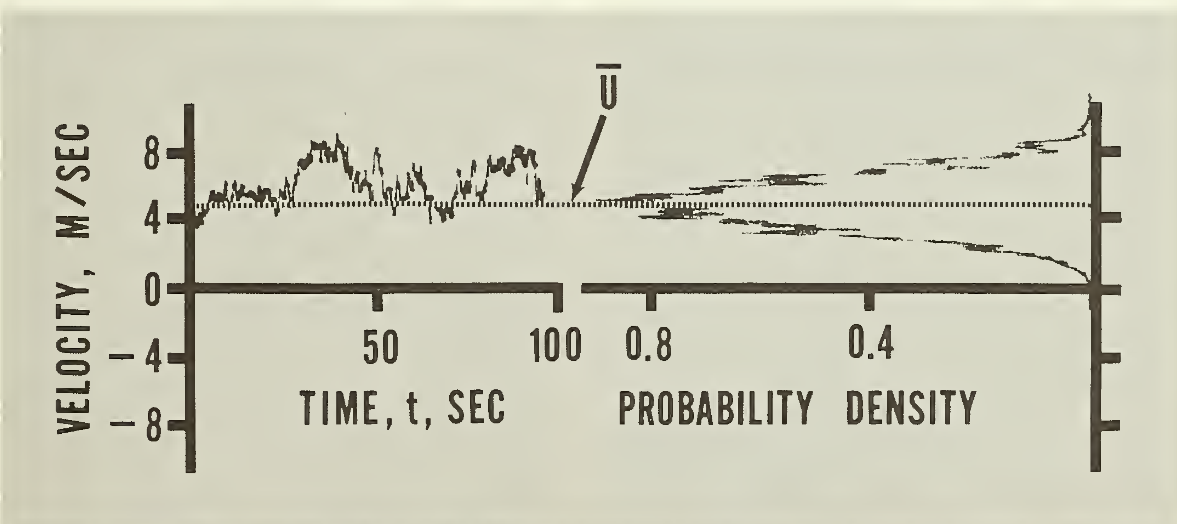


Fig. 2.—Probability density for above-canopy atmospheric turbulent flow. The velocity record was obtained with a directional propeller anemometer at 2.4 meters above a corn canopy of 1.6 meters average height.

instantaneous velocity, U, in the atmosphere above a corn canopy is shown in figure 2. The corresponding probability density is depicted by projection of the proportions of occurrences of velocity levels onto the velocity scale. The probability density shown in Figure 2 was obtained from analysis of the complete 5-hour turbulent velocity record. Again, it shows the proportion of total time the velocity magnitude spends near any given velocity level.

The turbulent-velocity probability density is an important analytical tool in turbulence research. It is important because it yields insight about more complex multivariate distributions as previously mentioned. In the simplest uniform turbulent flows, the velocity probability density may be found to have the familiar bell-shaped form of the normal distribution. In shear, boundary-layer, and canopy flows, however, the probability density is usually asymmetric, indicating its sensitivity to a non-uniform turbulent flow.

The single-component velocity probability density is still an incomplete description of a turbulent flow. Together with the single-component moments, including the MS-velocity, it leaves unmeasured the fineness of structure or *scale of turbulence.* It is possible for two turbulent flows with the same mean and MS velocities and with similar single-component probability densities to differ widely in the number of velocity fluctuations per unit time, on the average. Two such contrasting types of turbulence, besides reflecting distinct flow situations, can be expected to have significantly different transport effects. Certain types of multivariate distribution can quantify this structural difference, but the practical difficulties of obtaining them have been mentioned. The alternative is to use moments of these multivariate distributions—the correlations.

Correlations

THE correlation coefficient used in biometrical work measures how strongly one random variable is related to another. In turbulence analysis, the correlation does a similar job, but in less familiar ways. The turbulent-velocity correlation shows, on the average, how rapidly the velocity changes, indicating the degree of coherence between the velocity at one point in space or time and that at some other point in space or time. The degree of coherence at least depends on the separation of the two points in space or time. The term correlation is applied to two distinct types: the *autocorrelation* and *cross-correlation.* As measures of coherence, the autocorrelation reflects that of a random variable with itself, and the cross-correlation, that of one variable to another.

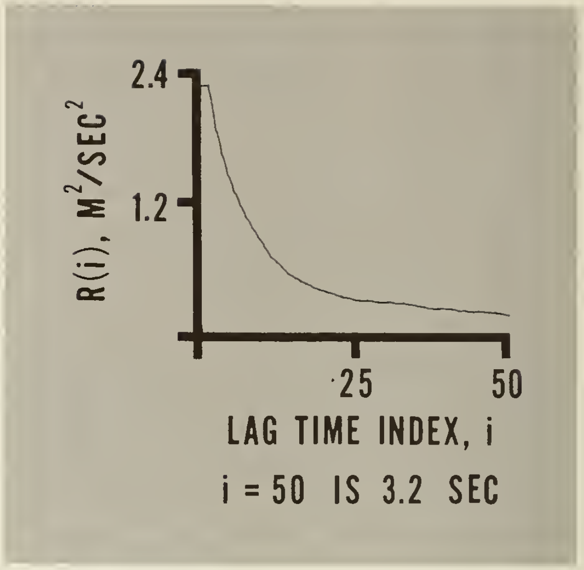


Fig. 3.—Velocity autocorrelation for the canopy turbulence of Figure 1.

Estimation of an autocorrelation function from experimental data can be illustrated as follows: First an *ordered* sequence of total flow velocity measurements, U_i, is obtained as for the mean and MS-velocities. If the mean, $\bar{U}$, is calculated, an ordered sequence of turbulent velocity values, u_i, can be obtained with the relationship $u_i = U_i - \bar{U}$. Assume that a large number, N, of turbulent velocity readings are tabulated. The autocorrelation, denoted here by R(i), is a function of i, the *lag index.* The lag index ranges through all integers from zero to M, where M is small compared to N. Coordinates are used as in Figure 3, with R(i) as ordinate and lag index, i, as abscissa. The turbulent-velocity autocorrelation function is estimated by computing an ordered sequence of values for R(i), one value of R(i) for each lag index value from zero to M. The values of R(i) are computed with the equation

$$R(i) = \overline{u_j \cdot u_{j+i}} = (1/N_i) \sum_{j=1}^{N_i} u_j \cdot u_{j+i},$$

the overbar denoting an averaged product. The integer N_i is the number of samples of the product

$u_j \cdot u_{j+i}$ available from the N observations, and can never be larger than N. The analysis begins at i=0 to obtain R(i=0), which requires each of the N observations to be squared and the average of these N squares to be computed as above. The result, R(i=0), is plotted on the grid of Figure 3 corresponding to i=0, noting that R(i=0) is equal to the variance. Next, R(i=1) is calculated by setting i=1 so that

$$R(i=1)=\overline{u_j \cdot u_{j+1}}=(1/N_1)\sum_{j=1}^{N1} u_j \cdot u_{j+1},$$

forming the products u_1u_2, u_2u_3, u_3u_4, etc., and finding the average as before. The result is plotted corresponding to i=1. The same computations are done for all other indices, i, from 2 through M, to eventually obtain a plot as in Figure 3. The resulting plot represents the autocorrelation function and is often called a *correlogram*. The correlogram in Figure 3 represents a 5-hour average, with M=100, for the turbulent velocity component of Figure 1. For this time autocorrelation, the lag index is directly proportional to time separation. The autocorrelation amplitude reflects the average coherence of any two velocity observations separated by the corresponding time interval, and it can take either positive or negative values.

A *cross-correlation function* is computed in essentially the same manner as an autocorrelation, except that the correlation-products are formed with paired values from two turbulent velocities. The equation for the cross-correlation, C(i), is

$$C(i)=\overline{u_j \cdot v_{j+i}}=(1/N_i)\sum_{j=1}^{N_i} u_j \cdot v_{j+i}.$$

As stated earlier, time and length scales of turbulent fluid motion are relatively large. Thus, despite the randomness of turbulence, experiments show the turbulent velocity does tend to persist over measurable times or distances. This is a critical difference between turbulent motion and some other types of random diffusive motion. For example, the molecular-bombardment mechanism producing Brownian motion is of such small scale that a person cannot possibly predict the details of a wildly wandering Brownian-particle path. In contrast, tracer particles in a turbulent fluid exhibit some degree of persistent motion, because of the preferred velocities imparted to them by large-scale fluid motion. Thus, while both Brownian and turbulent motion are random and inherently dispersive in effect, their diffusive mechanisms must be understood in different ways.

Brownian motion has been thoroughly analyzed using statistical and diffusion methods as described by Chandrasekhar (*8*). In turbulent diffusion, however, methods are used in which the correlation concept plays a vital role (*3,4,12,21*). Modern turbulent dispersion theory frequently uses *diffusion coefficients* which are derived from turbulent-velocity correlations. In fact, turbulent dispersion analysis forces a further distinction between types of correlation, the so-called *Eulerian* and *Lagrangian* distinction, which is discussed later. The MS- or RMS-velocity, the mean velocity, and the *integral time scale* or *integral length scale,* are also important ingredients of turbulent dispersion analysis.

The integral time scale is the maximum length of time, on the average, that a cell of fluid (or suspended particle) travels in a given direction with nearly constant speed. There are fairly simple prescriptions for calculating the integral time scale using the time correlation. This scale can be quickly estimated by inspecting the correlation such as in figure 3. The lag time where the correlation becomes nearly zero is roughly the integral time scale. The integral length scale can be determined in similar ways from a space velocity correlation.

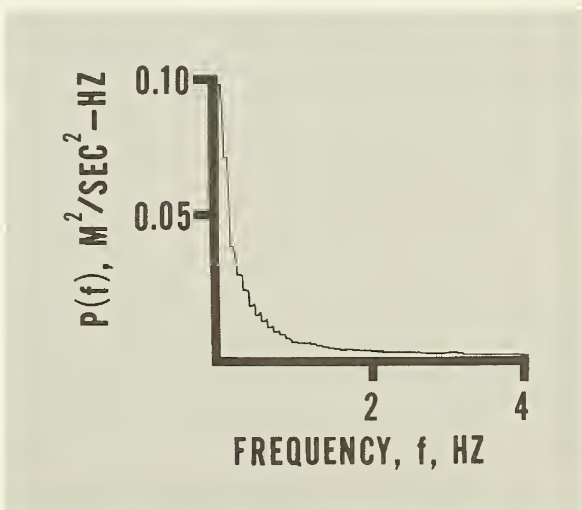


Fig. 4.—Velocity spectrum for the canopy turbulence of Figure 1 and corresponding to the autocorrelation of Figure 3.

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The structure of turbulence reflects the presence of eddies, or vortices, of varying sizes whose complex rotational flows intermingle with the mean flow. The correlation furnishes two important measures of eddy size, namely, the previously defined integral scale, and also the *microscale*. The value of the microscale depends on how sharply the correlation changes near zero lag, and as such estimates the characteristic size of eddies which are most active in viscous dissipation of turbulent energy as heat. The microscale is always smaller than the integral scale, which indicates the largest eddy sizes in a turbulent flow.

Aside from their uses in turbulence theory, estimates of these scales are very useful in aiding selection of instrumentation for experimental studies. For example, when both scales are small, flow sensors must be limited in size so that reliable measurements can be obtained.

Spectral Density

CORRELATIONS lead to another statistical tool, the *spectral density,* which provides an alternate view of the same aspect of turbulence as the correlation. In the literature, the spectral density is frequently called the *spectrum*.

The spectrum can be defined by the mathematical operation of *Fourier transformation performed* upon the correlation function. The Fourier transformation is similar to Fourier or frequency-domain methods used to analyze complex electrical signals or mechanical vibrations in engineering and series of weather observations in meteorology. The spectrum corresponding to a time correlogram is plotted as a function of *frequency,* or cycles per unit time, and that corresponding to a *space* correlogram is generally plotted as a function of *wavenumber,* or cycles per unit length. In either case, the spectrum is plotted as a function in the desired domain, wavenumber or frequency. Figure 4 shows the turbulent velocity spectrum corresponding to the autocorrelation in Figure 3. The spectrum amounts to a frequency analysis of the correlogram and can be applied to either auto- or cross-correlation, becoming more involved in the latter case.

Since discussions of Fourier analysis methods are available in the literature, (*5, 35*) space is not devoted to them here. The spectrum can be computed from the correlation fairly easily with a digital computer, recently developed fast Fourier-transform methods (*9, 10*) enabling on-line analyses in some cases. Turbulence spectra can also be obtained directly without use of the autocorrelation by means of fast-Fourier-transform methods, electronic filters, or special-purpose digital and analog spectrum analyzers.

In a physical sense, the turbulent-velocity spectrum maps the turbulent energy distribution over all "frequencies" of turbulent-velocity fluctuation. The turbulent velocity is sometimes conceived as composed of a large number of distinct sinusoidal velocity components, each of a different frequency. These components are assumed to be random in occurrence and phase. The energy content associated with each component is presumed to be a unique contribution, on the average, to the resultant turbulent velocity. No pure frequencies necessarily exist in reality, since the turbulent velocity is random and aperiodic, but this makes the spectral domain representation no less useful. To avoid misconception, the term *quasi-frequency* is sometimes used instead of frequency.

The spectrum also indicates how turbulent energy is partitioned among various eddy sizes. Large amounts of energy associated with low frequencies, or with low wave-numbers, indicate a turbulence having a preponderance of large eddies. In atmospheric turbulence, depending on the location and conditions, eddy sizes may range from only a few centimeters up to many kilometers in "diameter."

The spectrum is sometimes a convenient alternative to the correlation for interpreting turbulent flow structure, several important concepts having evolved directly from the spectral concept. Some turbulence parameters may be more readily derived from the spectrum than from the correlation.

Classification Properties

THE fundamental statistical tools which have been outlined enable definition of several important criteria for classifying turbulent flows or phenomena and the ways they are analyzed. The classification properties are (1) stationarity and nonstationarity, (2) homogeneity and nonhomogeneity, (3) isotropy and nonisotropy, and (4) the Eulerian and Lagrangian statistical properties.

Stationarity and Nonstationarity—A random variable is called *stationary* if its statistics are unchanging with time, implying that its mean, variance, higher-order moments, probability density, correla-

tion, and spectrum are the same regardless of the time at which observation of the variable is begun, the *time origin.* The correlation function will depend on lag time only and be independent of the time origin. A *nonstationary* random variable's statistics change with time and its correlation depends on time lag *and origin.* In a strict sense, the spectrum is defined only if the random variable is stationary. Observations of a sustained turbulent flow past a fixed point often exemplify a stationary random variable.

Homogeneity and Non-homogeneity—The statistics of an *homogeneous* random variable are uniform throughout the spatial region occupied by the system. Homogeneity is sometimes referred to as *spatial stationarity,* and the previous remarks about stationary systems apply similarly to homogeneous systems. Turbulent flow in the atmospheric surface layer and plant canopies is usually nonhomogeneous.

Isotropy and Non-Isotropy—The statistical properties of *isotropic* turbulence are independent of *direction.* For example, the statistics of isotropic turbulent velocities are identical in all three space dimensions. Turbulence theory is most highly developed for the isotropic case because of its much greater mathematical and experimental simplicity. *Nonisotropic* turbulence occurs in more complicated stratified, shear and boundary-layer flows. Mathematical and experimental analyses are much more difficult, since flow components in three space directions and their interactions may need to be taken into account.

Nonisotropy is typical of turbulent shear and open jet flows where turbulence is generated. In the atmospheric surface layer, where free and forced turbulence are being produced, flow is nonisotropic. Higher in the atmosphere, turbulence usually becomes more isotropic and homogeneous. Nonisotropic turbulence can generally be expected to occur in plant-canopy flows, since the canopy is within the boundary layer and contributes to turbulence generation.

Eulerian and Lagrangian Statistical Properties—*Eulerian* turbulence statistics are obtained from flow measurements made with fixed sensors. The tower-mounted cup anemometer which measures velocity as the wind moves past is an example. Turbulence statistics yielded by such data are the *Eulerian RMS velocity, Eulerian probability density,* and *Eulerian correlation* or *spectral density.* Eulerian statistics averaged over a *time* interval are called *Eulerian time statistics,* and those averaged over a *space* interval are *Eulerian spatial statistics.*

Lagrangian measurements require introducing the notion of a *fluid particle,* visualized as a small cell or fluid to which fluid mechanics laws apply. Lagrangian statistics concern the variations in fluid-particle velocity, temperature, or pressure, or in the states of groups of discrete particles, as they move through a region. Lagrangian statistics have not been as extensively studied as their counterpart Eulerian statistics, since direct Lagrangian measurements require laborious tracing of fluid-particle motion. Atmospheric measurements have been made by following trajectories of neutrally buoyant balloons by radar, theodolites, or other locating instruments, and tracer particles, such as smoke, are used in both atmospheric and laboratory research. Unfortunately, many trajectories or dispersion patterns must be observed to obtain reliable results, which is a very difficult task.

Attempts to derive Lagrangian statistics from the more accessible Eulerian quantities have not been successful for even the simplest flows. Some empirical relations have been established which are useful in practice (*13*) such as the fact that Lagrangian and Eulerian integral length scales are nearly equal and the correlations similar in form under some conditions (*21*). Aside from these limited results, the problem remains unresolved.

The relevance of Lagrangian statistics to the travels of "marked" particles makes them critical to understanding turbulent dispersion. Lagrangian methods supply a quantiative basis for analyzing turbulent transport of heat, vapor, gases, or discrete particles.

Measures of Stability

THE atmosphere near the earth's surface is seldom in a state of *neutral* thermal equilibrium. The air is usually either *statically stable* under temperature inversion, or else it is *statistically unsable.* In other than neutral conditions, turbulent energy arises from both the kinetic energy of the mean wind and the buoyancy effects caused by local temperature fluctuations. Buoyancy forces directly affect the vertical turbulent-velocity component. Turbulent energy produced by mean-wind shear enters directly into the horizontal, but only indirectly into the vertical,

turbulent-velocity component. These important factors generally demand that thermal stratification be considered in dealing with atmospheric turbulence and dispersion.

The Reynolds number, a dimensionless ratio of inertial to viscous forces in flow, is often used in analyzing homogeneous fluid flow. High Reynolds numbers indicate favorable conditions for turbulence. However, in the *nonuniform* flow of the atmosphere, an index often used is the dimensionless Richardson number. There are both *flux* and *gradient* Richardson numbers. The *flux* Richardson number is the ratio of turbulence-energy production by buoyancy forces to that due to mean-wind shear. The gradient Richardson number is the ratio of buoyancy to inertial forces. Either number basically indicates whether the energy supplied by the mean wind is adequate to maintain vertical turbulence against gravity.

Richardson numbers have been long used as indices of stability, but the Richardson number is not a criterion for the onset or cessation of turbulence. Physical conditions other than those represented by the Richardson number must create the instabilities leading to turbulence. The Richardson number indicates only whether the resulting turbulence will be self-sustaining.

Since the flux Richardson number is difficult to obtain from experimental data, the gradient Richardson number is more commonly used. In some cases, a simplified parameter, the *stability ratio,* is a satisfactory stability measure (*33*).

Richardson numbers are indicative of the strength of atmospheric turbulent transport activity under given conditions. Recent experiments have similarly shown that the stability ratio may serve as an index of the degree of chemical drift in pesticide application.

TURBULENCE MEASUREMENT

DEVELOPMENTS in the theoretical areas of fluid mechanics and micrometeorology have depended on and created need for significant advances in instrumentation. The study of atmospheric and plant-canopy turbulence imposes some particularly stringent requirements on such instrumentation. It must reliably detect fluctuating variables and retain its reliability during prolonged atmospheric data acquisition when environmental conditions may be adverse. At the same time it must be easily operated and relatively inexpensive to make its use feasible in extensive arrays or networks.

Three primary state variables of fluid flow are pressure, temperature and velocity. Whether all of them, and possibly others, such as radiation or humidity, need to be measured depends on the nature of the investigation. Some synoptic weather observations almost always accompany any experiment. This discussion will be confined to instrumentation for the primary state variables.

Pressure

MERCURY and aneroid barometers, and recording microbarographs, are long-established in meteorological research and observation, being depended upon for synoptic data and for standardization. In recent years, differential pressure transducers comprising sensitive resistive, capacitive, or inductive bridge systems have come into use. Their rapid dynamic responses enable study of local pressure fluctuations important in some detailed micrometeorological research.

Temperature

VARIOUS types of liquid-in-glass (typically mercury), remote-indicating, and recording thermometers are often used for synoptic observations. However, extensive thermocouple networks with recording systems are usually required for micrometeorological research. In some cases, simple thermocouples or thermocouple probes provide acceptable accuracy and precision. However, when high-accuracy temperatures or temperature gradients are needed, a more elaborate system is essential, including provision for shielding thermocouples from radiation, which can cause significant error. Shielded temperature sensors are set up in arrays for horizontal or vertical temperature profiles outside and within vegetative canopies (*26*).

Velocity

SELECTION of air-velocity instrumentation first of all depends on whether synoptic data or detailed turbulence measurements are required. The number of measuring stations, proximity to the ground and vegetation, turbulence integral scale, and equipment cost further condition the final choice. Mechanical or electromechanical sensors are very

adequate for measuring large-scale atmospheric turbulence having relatively slow velocity changes. Studies of small-scaled turbulence require more rapidly responsive systems using electronically controlled sensors. Response capability up to about 1,000 Hz (cycles per second) is usually considered adequate for almost all atmospheric work. In many cases much lower response is sufficient.

Cup anemometers are usually standard at weather stations for measuring total horizontal wind velocity. Because of their mechanical size, they cannot follow rapid velocity fluctuations, but they are quite suitable for studying large-scale turbulence. Their starting-threshold wind velocity is normally not less than 13 meters per minute. Because of these factors, cup anemometers must not be located too near the ground. However, some small cup anemometers recently developed for micrometeorology are usable nearer the ground and in vegetative canopies if operating space is not too restricted. Cup anemometers have the advantage of linear velocity response, but since they are omnidirectional, an auxiliary direction-indicating device such as a vane or bivane is essential.

Propeller anemometers are extensively used in research, offering the advantages of linear response and direct velocity component resolution. This feature makes them particularly useful for detailed studies of large-scale turbulence. Starting thresholds of propeller anemometers are typically about 13 to 16 meters per minute. Their mechanical inertia and size limit them to measurements of slow changes in wind velocity and restrict their application near the ground or within canopies.

The *sonic anemometer* offers direct velocity-component resolution and fast linear response (*23*). Each sensing axis comprises at least two sonic transducers facing each other along a line parallel to the desired velocity component. Sound waves are simultaneously transmitted and received with and against the wind velocity. Electronic detection and comparison of the two Doppler shift effects ultimately yield the total velocity component. Three such systems are required for three-dimensional measurements, and the separation between transducers places a lower limit on the measureable eddy size. At present sonic anemometers are electronically complex and expensive but are nonetheless advantageous where conditions and resources permit.

Hot-wire and *hot-film anemometers* sense flow by continuously transferring a small amount of heat to the fluid. Generally, a servo-amplifier system heats the sensor electrically to maintain a constant temperature much higher than ambient temperature. Air-velocity changes alter the sensor's heat transfer rate, but the servo-amplifier automatically adjusts heating to hold temperature steady. The heating voltage is a non-linear measure of the velocity, but the response can be linearized electronically.

Hot-wire and -film anemometers are highly sensitive, can be adapted for velocity-component resolution, and have very fast response—features suiting them to studies of all scales of turbulence. They can readily measure air velocities down to about 4 meters per minute, which with their very small size, allows operation within dense plant canopies close to the ground. However, hot-wire sensors are fragile and susceptible to contamination by foreign matter, which may cause calibration shift. Hot-film sensors are not as vulnerable, because the sensing film is supported by a larger dielectric fiber substrate which makes the sensor more rugged and less subject to contamination. Mechanical guarding, care in handling, and occasional calibration checks can overcome these problems. Hot-film anemometers have been successfully used under rainfall conditions (*31*).

Hot-film sensors are set in multiple array for three-dimensional resolution of atmospheric turbulence. Analog or digital computers are used to derive velocity-components from the multisensor data. Special sensor arrangements, or auxiliary electromechanical or electronic systems, must be used to enable removal of flow-direction ambiguities from the results. These methods are essential for high-intensity atmospheric and plant-canopy turbulence where major changes in flow direction occur and can introduce significant error in hot-film measurements.

Recent advances in hot-wire and -film system design have improved their stability, reliability, and operating simplicity. Cost per channel has been reduced such that multi-sensor arrays essential for micrometeorological studies are feasible.

Thurtell, *et al* (*45*) have developed a *pressure-sphere anemometer* for three-dimensional velocity measurements in micrometeorological studies.

DATA PROCESSING

THE heavy data-processing requirements of turbulence analysis and micrometeorology are necessarily met with electronic computers. Many operations are fairly routine, such as converting or correcting raw data or computing humidities from wet- and dry-bulb temperature observations. For detailed turbulence analysis, statistical processing can be done with the adaptation of available programs, such as the fast Fourier transformation. Careful selection of sampling intervals and observation times is particularly important for reliable correlation and spectral computations. There are also other pitfalls which can introduce problems in digital analysis of data. Guides such as Bendat and Piersol (*5*) are used to help assure successful analyses.

TURBULENT DISPERSION

TURBULENT dispersion processes are important facets of plant-canopy micrometeorology. Their role in transport makes them the object of many plant microclimate and plant protection studies. Both molecular and turbulent transfer processes are active in the atmosphere, but turbulent transport is nearly always predominant, as mentioned before.

The action of turbulent dispersion can be visualized by observing a puff of smoke or the plume from a factory stack. Advective effect causes the smoke to be carried along with the prevailing wind, and turbulent dispersion is evident in the expansion, distortion, and wandering of the plume or cloud. The Lagrangian, or indirectly the Eulerian, MS–velocity and integral scale roughly indicate the degree to which these processes will occur.

A fundamental goal of turbulent dispersion theory is to predict as functions of time and location, the probable displacements, concentrations, and dosages of transported substance, *dosage* being the cumulative amount of substance delivered to a specific location. Although concentration is frequently treated as an average quantity, it must be borne in mind that it too is a fluctuating variable (*16*). Atmospheric turbulent dispersion theories fall into two major classes, either *transfer* or *statistical. Transfer* theories are generally based on a physical model which assumes that the local turbulent-transport rate is proportional to the local gradient of concentration of dispersing substance. The proportional factor is called an *exchange coefficient* or *eddy diffusivity.* Explicit mathematical form must be established for the eddy diffusivity based on measurable properties of the turbulent flow. A principal shortcoming of transfer theories is failure of the assumption of gradient-type diffusion for many turbulent flows. Gradient-type diffusion can result from small-scale turbulence, but large-scale fluid motion induces strong convective action in addition. The *statistical* theories, on the other hand, do not depend on a particular physical diffusion model. Instead, they represent statistically the excursions of marked fluid elements in terms of derived or measured characteristics of turbulent motion.

Although transfer theories are not correct in all details, they offer practical semiempirical relations for analyzing turbulent dispersion. In contrast, though the statistical theories date back almost as far as the transfer theories, their application, and the accompanying understanding of atmospheric turbulence structure, have only recently undergone rapid development. The modern statistical studies have bypassed several transfer-theory difficulties, extending our insight into turbulent transport mechanisms. But much work remains in bringing about their more extensive application. These theories particularly need development in their advective and nonhomogeneous flow aspects, conditions which are inherent to plant-canopy flow.

Either analytical method frequently uses the familiar differential equations of heat-conduction and diffusion theory. Statistical theories derive their dispersion coefficients from Lagrangian, and sometimes Eurelian, velocity correlations or else from directly measured statistical parameters.

Turbulent transport of heat, gases, and vapors may be represented by a fluid-particle dispersion model. Solid particles or liquid droplets, however, are of much greater density than air, and, despite viscous coupling, cannot follow the sharpest turbulent velocity changes (*15, 21*). Furthermore, they are subject to gravitational and other external forces causing them to drift and possibly alter their turbulent-transport behavior. Any turbulent-dispersion theory needs modification to account for these effects.

The eddy-transfer or eddy-correlation method is sometimes used to measure the average flux of transported substance past a fixed point over a period

of time (*48*). For example, the simple time correlation of vertical flow velocity with temperature at some location measures the average upward heat transfer at that point. Such measurements can be made with relatively simple equipment.

SOME CURRENT RESEARCH

FLUID dynamics research in the laboratory and atmosphere is increasingly being directed to the structure and dispersion processess of turbulent shear flows and boundary layers. Laminar-turbulent flow transition and Eulerian correlations at two or more points in time and space are also being studied. More comprehensive Lagrangian data and Eulerian-Lagrangian relationships are being sought, but progress on this difficult problem will be slow. Improved methods of obtaining Lagrangian data must be developed if more rapid advances are to be realized.

In work concerned with micrometeorology and plant climatology, there are continued efforts to devise and improve instrumentation for measuring the highly variable conditions of the atmosphere. Several developments in anemometry and some new flow-sensing devices show promise for plant-canopy turbulence studies. With these advances, more extensive data are being obtained on the vertical profiles of flow, temperature, humidity, carbon dioxide, and radiation in vegetative canopies. It is likely that similar efforts on horizontal or space-averaged profiles will be forthcoming.

The fluid flow mechanisms underlying observed canopy profiles are receiving greater attention. The effects of soil roughness and topography and of canopy structure are being investigated (*7,22,27*). Methods of analyzing the geometrical form of the canopy and topography are under consideration (*19,32*).

A long history of research on public and industrial health problems, pollution, and atmospheric dispersion has yielded an extensive technology of air sampling. Many air sampling devices, including filter and impaction units and gas analysis systems, are readily adaptable to agricultural microclimate and pollution research. This technology is promoting efforts to measure dispersion of particulates, droplets, vapors, and gases within and near canopies. Intensive interest has arisen on the relation of forest cover to pollution control, and how the atmosphere influences spreading of insect and disease damage over plant populations.

S. M. Corrsin (*11*) has authored a very readable review of the physics of turbulence. Immediately following Corrsin's article in the same journal is another on microclimate and bioclimatology by Biel (*6*). A number of books also cover theoretical and experimental results on turbulence and turbulent dispersion for atmospheric and other types of flow (*17,18,20,21,28,33,36,37,39*). Several books and articles discuss vegetative microclimate and the surface turbulent energy budget more execlusively (*1,14,29,30,33,38,40,46*). Panofsky and Brier (*35*) give a thorough review of statistical methods useful in meteorology.

Some of the complexities of turbulent flow processes have become evident. The added intricacies of turbulent transport phenomena and of atmosperic surface-layer and plant-canopy flow scarcely ease the challenge. However, long-time investigators working chiefly with pipe and wind tunnel flows consider atmospheric research to be one of the most exciting areas for new developments in our understanding of turbulence. Atmospheric systems, despite their apparent added complexity, avoid some of the technical restrictions closed systems impose. The statistical methods of analyzing and modeling turbulence, while by no means the singular or ultimate ones, are becoming standard and highly useful in many studies. But the work and contributions of all disciplines and technologies will be essential to meeting the continuing critical need to improve the agricultural and human environment.

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SCIENTISTS AT WORK

THE essential wildness of science as a manifestation of human behavior is not generally perceived. As we extract new things of value from science, we also keep discovering parts of the activity that seem in need of better control, more efficiency, less unpredictability. We'd like to pay less for it and get our money's worth on some more orderly, businesslike schedule. The Washington planners are trying to be helpful in this, and there are new programs for the centralized organization of science everywhere, especially in the biomedical field.

It needs thinking about. There is an almost ungovernable, biologic mechanism at work in scientific behavior at its best, and this should not be overlooked.

The whole scientific enterprise must be arranged in such a way that the imaginations of different human beings can be pooled, and this is more a kind of game than a systematic business. It is the abrupt, unaccountable aggregation of random no-

tions and intuitions, known in science as good ideas, that the high points are attained.

The most myterious aspect of difficult science is the way it is done. Not the routine, not just the fitting together of things that no one had guessed at fitting, not the making of connections—these are merely the workaday details, the methods of operating. They are interesting, but not as fascinating as the central mystery, which is that we do it at all and that we do it under such compulsion.

I don't know of any other human occupation, even what I have seen of art, in which the people engaged in it are so caught up, so totally preoccupied, so driven beyond their strength and resources.

Scientists at work have the look of creatures following genetic instructions; they seem to be under the influence of instinct. They are, despite their efforts at dignity, rather like young animals engaged in savage play. When they are near an answer, their hair stands on end, they sweat, they are awash in their own adrenalin. To grab the answer, and grab it first, is for them a more powerful drive than feeding or breeding or protecting themselves against the elements.

It sometimes looks like a solitary activity, but it is as much the opposite of solitary as human behavior can be. There is nothing so social, so communal, so interdependent. An active field of science is like an immense intellectual anthill: the individual almost vanishes into the mass of minds tumbling over each other, carrying information from place to place, passing it around at great speed.

In the midst of what seems to be a collective derangement of minds, with bits of information being scattered about, torn to shreds, disintegrated, reconstituted, engulfed in an activity that seems as random and agitated as that of bees in a disturbed part of the hive, there suddenly emerges, with the purity of a slow phrase of music, a single new piece of truth about nature.

In short, it works. It is the most powerful and productive thing human beings have learned to do together in many centuries—more effective than farming, or hunting and fishing, or building cathedrals, or making money.

It is instinctive behavior, in my view, and I do not understand how it works. It cannot be prearranged in any precise way; the minds cannot be lined up in tidy rows and given directions from printed sheets. It cannot be done by instructing each mind to make this or that piece for central committees to fit with the pieces made by other instructed minds. It does not work this way.

—Dr. Lewis Thomas, *dean of medicine, Yale University, in The New England Journal of Medicine 288, 307 (1973)*.

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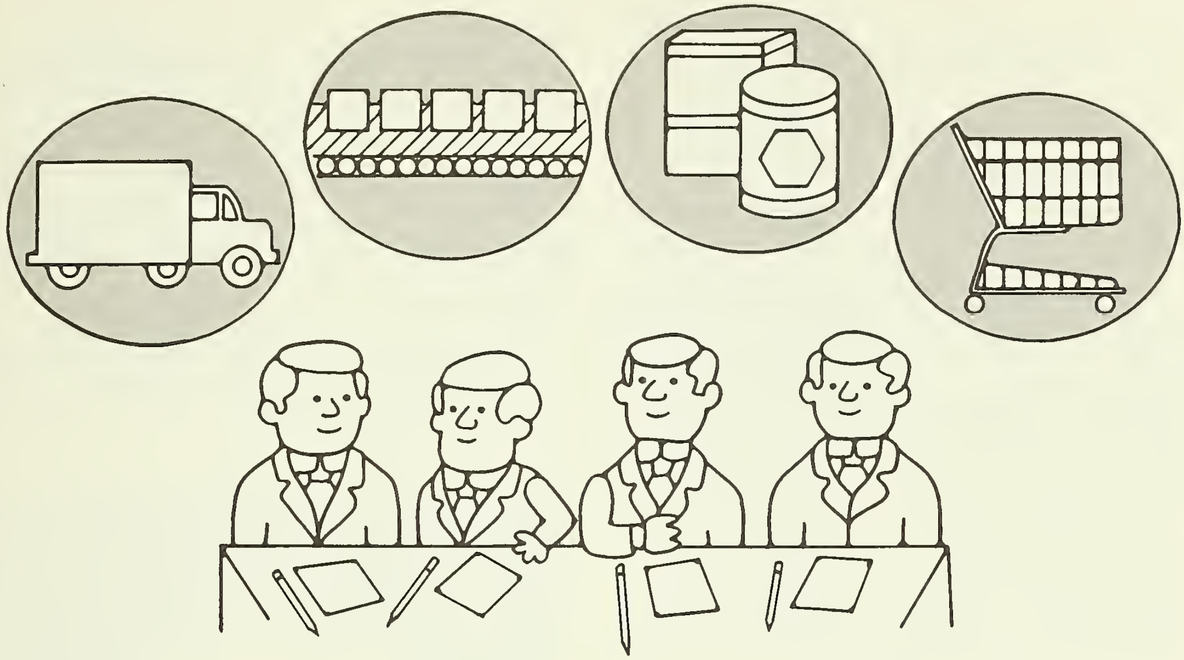


VIEWS ON STRENGTHENING MARKETING ECONOMICS RESEARCH

H. B. METZGER

In 1971, a noticeable waning in the enthusiasm for marketing research and perhaps a decline in its effectiveness prompted USDA's Cooperative State Research Service to initiate a study of the position and problems of marketing research at the State agricultural experiment stations. It was hoped that such a study would aid in strengthening future marketing research programs and make them more useful to clientele.

The study was conducted by Homer B. Metzger, then chairman of the department of agricultural economics at the University of Maine, during his sabbatic term as principal agricultural economist with CSRS in 1971–72. Dr. Metzger surveyed station directors, heads of departments of economics, and research economists. His findings are reported in Marketing Research at State Agricultural Experiment Stations: Past, Present, Future, *a 148-page publication of CSRS.*

This article excerpts certain passages of the bulletin, including the recommendations and conclusions.

THE impetus for expanded marketing research at State agricultural experiment stations was provided in 1946 when U.S. Public Law 733 was enacted. Expansion was reinforced in 1955 by Public Law 352, which authorized the continuance of the requirement that not less than 20 percent of Federal

funds appropriated for the SAES be used for marketing research, and no more than 25 percent be used for cooperative (regional) research. While the 20 percent marketing requirement always has been met on a national basis, a substantial percentage of the States fail to meet the requirement each year; other States spend sufficiently above requirements to offset it.

During the past 25 years of emphasis on marketing research, research activities evolved from descriptive to analytical. The analytical moved from firm functional efficiency to market structure and organization. The use of computers and economic models permitted analyses of complex relationships and the impacts of marketing alternatives on firms and industries. Regional research activities were widespread and productive, but suffered from lack of close-knit coordination. A continual and substantial shift to the technology of marketing and a decline in the economics of marketing research characterizes the period.

Attitudes Toward Marketing Research

CURRENT attitudes toward marketing research were determined by surveying station directors, heads of agricultural economics departments, and research economists.

All three groups generally agreed that the principal obstacles to an expanded marketing economics research effort are: (1) lack of professional interest, (2) production orientation of the station, (3) restrictions on funds and personnel, (4) lack of public interest, (5) restrictive definition of marketing, and (6) difficulty doing marketing research.

The survey was specifically designed to determine the current effectiveness of marketing research and to elicit suggestions for organizing a more meaningful effort. The following comments are typical of those received from all groups.

Marketing research has been mostly descriptive; most of the publications interest only other economists.

The glamour of marketing research has been supplanted by interest in basic research, in the biological sciences, and concerns for the environment, natural resources, and rural development.

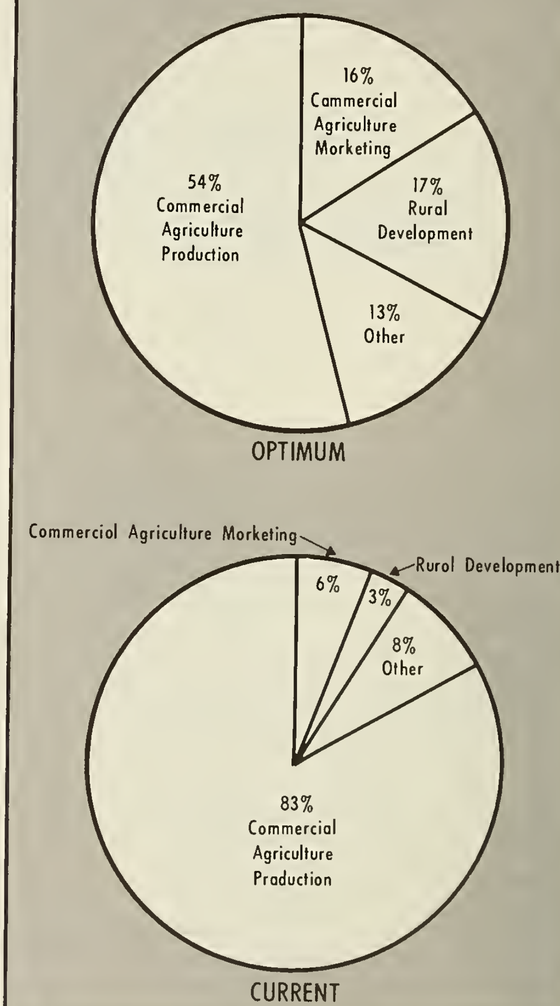
There is a need for new strategies to make marketing research more relevant in an emerging marketing system of greater complexity and sophistication.

More emphasis is needed on broader, well coordinated projects involving a team effort on high priority areas.

Nobody knows for certain what the optimum allocation of research resources ought to be. There are ready and urgent needs in so many areas that undue concern about any preconceived optimum is of secondary importance.

The major obstacle to optimum allocation of resources is the difficulty always faced in hiring people to fulfill a specific purpose when the purpose changes faster than do people.

Figure 1- CURRENT AND OPTIMUM ALLOCATION OF FUNDS BY RESEARCH AREAS, SAES, 1972 SURVEY OF DIRECTORS



Good marketing research is difficult to do and equally difficult to distribute to the public.

Recommendations and Conclusions

THE marketing research effort at State agricultural experiment stations is languishing. The marketing economics research effort, in particular, lacks vigor.

Total expenditures on the economics of marketing research have been declining relative to total marketing expenditures, and total expenditures for marketing research have been declining relative to total station expenditures. Expenditures of Federal (Hatch Act) funds on marketing research are nationally at minimum levels required by law, and many States fail to meet requirements. Heads of departments of agricultural economics would shift substantial funds out of marketing if restrictions on the use of funds and personnel were removed. Manpower devoted to marketing research has been declining, contrary to recommendations of the joint USDA–SAES Task Force on Marketing and Competition.

Marketing research efforts are fragmented and narrow in scope. There are about 1,800 projects in 25 different fields of science, and nine different national research goals. Yet funds are concentrated heavily in three problem areas for economics research and four problem areas for noneconomics research.

SAVINGS FROM RESEARCH

Both private industry and Government research have provided much of the technological means and economic guidelines for marketing adjustments to help offset rising labor costs over the past 25 years.

Consumers benefited from marketing research through estimated savings in food costs of $9.6 billion ($193 per family) annually during 1947–1970. The total marketing research expenditures (investments) by State agricultural experiment stations during that period amounted to $200 million. If this research of the SAES is considered to have caused only 1 percent of the above estimated savings on food costs, then returns on the research funds expended were substantial, with consumers receiving an average annual return of 42 percent on this investment.

There are some strengths in marketing research on which to build an effective program.

Expenditures of $21 million annually on marketing research are sufficient to provide meaningful impact. Both Federal and State funds for marketing research have been increasing. Station directors indicate they would shift substantially more funds

TABLE 1.—*Reasons stations are spending only 6 percent of total research funds on marketing, by respondent*

Reason	Station director	Dep't head	Research economists	All
		Percent of responses		
Don't know	1	13	7	7
Difficulty doing marketing research	25	16	20	20
Lack of public interest	26	20	16	19
Stations' production orientation	7	16	26	19
Lack of professional interest	14	16	13	14
Restrictive definition of marketing	14	8	8	10
Other	13	11	10	11

TABLE 2.—*Critical, researchable problem areas in marketing economics, by respondent*

Problem area	Director	Head	Economist	All
		Percent of responses		
Organization and structure	19	34	27	27
Systems efficiency-operation, pricing	26	30	28	28
Market development	25	12	10	13
Competitive position	9	11	8	9
Supply-demand-price	10	3	6	6
Firm efficiency, management	3	3	11	8
Other (policy, rural development, consumer, margins, technical development, grades)	8	7	10	9

into marketing research if all restrictions on funds and personnel were removed.

Ratings of the research effort indicate average performance in marketing economics compared with other station units involved in research. Some adjustments have been made to fewer numbers of projects and to shifts in projects among problem areas being researched.

There are numerous obstacles to an expanded, more effective research program. Directors, department heads, and research economists agree that the principal obstacles to an expanded marketing economics research effort are lack of professional interest and difficulty doing marketing research.

A more effective research effort could be achieved through making changes in the planning and coordination of research at the station and the regional levels. Greater cooperation among disciplines, greater emphasis on problem solving, reactivation of regional planning committees, and use of regional coordinators are indicated needs.

Since some major changes in organization in respect to conducting research will be required if research in marketing economics is to be strengthened and expanded, it is recommended that consideration be given to the following:

Establishment of marketing research centers or institutes at selected stations.

In view of the low rating given marketing research on "scope and size" by directors, and the apparent divergence between directors who would increase and department heads who would decrease funds devoted to marketing research, the best alternative to correcting the deficiency would appear to be the creation of institutes or centers. Such arrangements are also implied in view of (a) the fragmentation of the research, (b) the strong expression of need for central coordination and regional research planning committees, (c) the need for greater contact with industry, and (d) the need for more problem-solving research.

Establishment of much closer working relationships with government agencies and other identified clientele.

Such arrangement is implied in view of the expressed lack of public interest in marketing economics research, and the indicated difficulty of doing economics research. These were principal obstacles cited as preventing an expanded research effort. Such factors as the low "payoff" of research, the privileged nature of the needed data for analysis, and the controversial nature of the subject-matter are related to the difficulty of doing research. Closer working relationships with a known clientele could remove these obstacles or ameliorate them.

Shifting more rapidly into new problems areas, particularly into marketing organization and structure, and marketing systems efficiency research.

These are critical problem areas needing research, and their attack should serve to bolster public sup-

port for, and stimulate professional interest in, marketing economics research.

Reorienting the missions and goals of the Stations and adopting personnel policies to create more staff positions in marketing economics.

Such action is needed to help overcome funds and personnel restrictions which have been identified as important obstacles to resource reallocation and expanded marketing research effort.

Affirming that CSRS Marketing Research Guidelines are meaningful and the intent of Congress.

A substantial segment of the station directors and economists indicated that the guidelines are a limitation in allocating resources and are obstacles to expanded research efforts. Under present law, further extension into production-related activities would seriously challenge the meaning of marketing and the intent of Congress.

WHAT FORM OF AGRICULTURE? A SOCIAL-POLITICAL-ECONOMIC ISSUE

WITH a representative government, the people can have any kind of agriculture they want. And I think they will insist on having what they want.

Suppose for a moment that the large-scale farming units are more efficient than family farms. People are asking whether, in as affluent a country as the United States, efficiency should be the sole criterion for the form of agriculture we are to have. We now supply ourselves with food—the best diet ever, anywhere—with about 16 percent of our income. If we stay with the family farm and improve its efficiency, the percentage of income spent for food will go still lower. Should we adopt a new and greatly different system so as to drive food costs down even faster? Should we sacrifice a form of agricultural production that has served us well, better than any other country has ever been served?

This is a fair question. The answer to it is properly social and political as well as economic. I believe this to be a major farm policy issue of the decade ahead.

And I do not think our agriculture need be or will become monolithic, relying on one managerial concept only. We are a pluralistic country socially, politically, and economically. The fact that the trend has been in the direction of large-scale units does not mean that this trend must be extended until it embraces all of agriculture. Nor does it mean that large-scale farming units should be abolished. I see no good reason to prevent us from having a farming system that is partly large-scale and partly family farms. Those who believe in market competition should also believe in the appropriateness of competing institutional forms.

For most American agriculture, the family farm can continue to be the major organizational form:

If it is permitted the flexibility that will allow the efficient use of modern technology and management.

If it is provided with good research, education, and credit.

If it makes wise use of the principles of cooperation.

If it has access to the market.

If it continues to enjoy the good will of the public.

As I judge the mood of the American public, this is the wish and the intent.

—Don Paarlberg, *Director, Agricultural Economics, U.S. Department of Agriculture, from his comments before the 1973 Outlook Conference, Washington, D.C.*

SCIENCE NOTES

BEET THINNING

MECHANICAL thinning of beets—one of the last links in the total mechanization of the industry—is on the upswing, made possible by improved weed control practices.

A mechanical thinner that uses an electronic sensor depends on weedfree beets to do an effective job. When a beet—or weed—passes between the electrodes of the sensor, a knife is triggered that clears the row for a set distance ahead of the beet. The process is repeated when the senor approaches the next vegetation in the row. Unless the beets are weedfree, the result is a thinned row containing both beets and weeds.

Extensive herbicide testing at Oregon State University has led to herbicides that make mechanical thinning practical. By incorporating the herbicides into the soil prior to planting and following with another application prior to thinning, weeds are effectively controlled.

Hand weeding and thinning runs as high as $100 an acre in some fields, compared to about $15 an acre for herbicides and their application and an additional $15 an acre for mechanical thinning.

A CROWDED WORLD

A teaspoonful of soil from temperate regions teems with some 5 billion bacteria, 20 million actinomycetes, 1 million protozoa, and 200,000 algae and fungi.

ALFALFA CLONES INDICATE POLLUTION

Nine clones of alfalfa that are resistant to air pollution and five clones that are highly susceptible have been developed at the Agricultural Research Center, Beltsville, Md. They are being released to scientists throughout the country for use as bioindicators of plant stress. Resistance to air pollution can be measured in alfalfa by its degree of tolerance to ozone injury. The tolerant plants are also being analyzed in the laboratory for their nutritive value and their resistance to leaf diseases and insects.

COSTLY POISON

Each year in the United States poison ivy and poison oak cause nearly 2 million cases of skin poisoning and other skin irritations, resulting in an estimated loss of 333,000 man-days of work.

METRICATION MATTERS

Remember this name: American National Metric Council. It is the nongovernmental body now being set up—and seeking subscription or grant funds from the public—to pull together the great network of activities that will be involved in the U.S. metric changeover when and if it comes. The Council, which has the approval of the American National Standards Institute, will also maintain close liaison with the official National Metric Conversion Board that is to be established under currently proposed metrication legislation.—*Commerce Today,* Vol. III, No. 9, 1973.

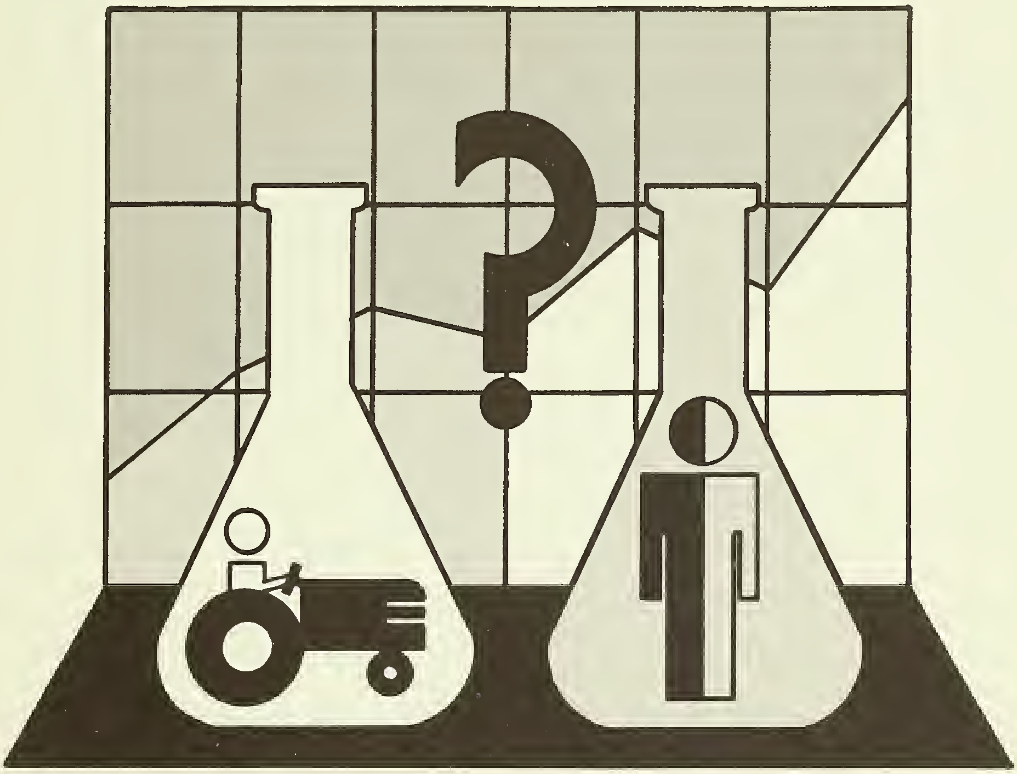
THAT AMAZING AMAZON

A team of Brazilian and U.S. hydrologists have used a new technique to measure the flow of the Amazon. Taking measurements from a moving boat rather than at fixed stations, they determined the rate of flow to be 4 billion gallons per minute. The measurement was made about 400 miles upstream from the mouth at the river's narrowest part, a little over 1.5 miles wide and 235 feet deep. The average flow of the Amazon is about 10 times that of the Mississippi. The Amazon accounts for about 15 percent of all fresh water discharged into the oceans by all the rivers of the world.

PROTEIN FROM SUGARCANE WASTE

A process has been developed that can turn cellulose of waste sugarcane bagasse into a powder having a crude protein content of 50 to 60 percent, according to the Division of Engineering Research at Louisiana State University. Cellulomonas species of bacteria are grown on the bagasse in a fermentation tank. Inorganic ammonium salts are used as a nitrogen source. A high protein suitable for animal feed is produced.

ECONOMIC RESEARCH TRADE-OFFS BETWEEN
EFFICIENCY and EQUITY



QUENTIN M. WEST

AGRICULTURAL economic research in the United States has traditionally focused on farm production and marketing efficiency. In the future it must give more attention to equity.

Americans will certainly maintain their interest in producing things more efficiently. But, it is a healthy sign that they are also becoming more interested in making sure that changes are made fairly, justly, and impartially.

While there has been an increasing amount of agricultural economic research directed toward the problems of equity, there has not been enough. While I could document this research, I think it more useful at this point to consider seriously our overall research policy and try to reach some conclusion about whether it has adequately come to grips with the economic and social issues pressing upon us today.

In the long-run, society will generally cease to support investments which it believes do no serve the broad interests of the public. Society will be concerned more and more with those issues which go beyond "efficiency."

There are those who say our production-oriented research, supported by public moneys, has been way off base. Some of it has been. Some of it has been too narrow, because it has largely ignored a very large set of consequencies—the human costs and returns. So in certain instances, our detractors have

This article is essentially the same as a paper presented at the annual meeting of the Southern Agricultural Economics Association, Feb. 7, 1973, in Atlanta, Ga.

reason to complain and to demand change. I submit, however, that we should not abandon what has been good and fruitful research, but rather we should broaden our area of concern to include all the consequences of change.

For example, development of cotton varieties adapted to the Southwest along with the development of irrigation there, led to lower cost of producing better cotton. This also led to the wholesale displacement of people in the Southeast as cotton production moved westward. Whole communities in the Southeast were left with unemployed and underemployed farmers and farm workers. Many of the displaced migrated to the cities in search of jobs that were nonexistent for which they were not prepared. Yet we did not study this impact as soon as we should have.

"*Inconveniences*" *of Change*

THERE are many examples where our attempts to increase the output of food and fiber have generated environmental problems and socioeconomic inequities. The point is that we must focus more attention on who gains and who loses, by when, how, and by how much. We must be able to anticipate and possibly forestall the "inconveniences" associated with change.

We have largely avoided these problems because they are controversial and therefore dangerous to our programs. Too, we have not sufficiently developed our economic theory, conceptual bases, analytical techniques, and our data base to accommodate these problems. But conflicts can be resolved only if adequate information about alternatives exists and is available equally to all those concerned. Research has the important responsibility in making these alternatives known.

We can expect the interdependencies of our economy to grow in step with economic progress. This will increase the likelihood that the gains and losses of new technological developments will not be shared equally by all members of our society. If we do not shift with the times, and begin addressing more fully this problem of equity, we will face a mounting backlog of problems which can overwhelm our best efforts to build a strong rural economy in America.

It is, of course, unfair to single out our agricultural economics research system as being inadequate in its attention to modern issues of equity. A recent Economic Research Service study showed that Federal spending on human resource development disproportionately favors metropolitan areas over nonmetro areas. For example, nonmetropolitan counties account for 66 percent of all substandard housing units but receive only 16 percent of all Federal housing assistance. A similar situation exists in the areas of education, health, manpower training, and others.[2]

Today's Research Priorities

THE formation of public policy is highly dependent on the quantity and quality of knowledge available. It is our research institutions that add to this stock of knowledge. So, if we are to have the knowledge required to make appropriate public policy, our research institutions must better meet this challenge.

Returns to the commercial agriculture sector are as important today as ever. But, we must now look beyond farm gate questions and do a better job of representing the entire society.

On one hand, we need to accelerate our efforts to measure the impact of public decisions on commercial agriculture. This includes a wide range of issues including those on the use of pesticides relating to the preservation of our environment. These decisions impact substantially on the ability of our food and fiber system to produce efficiently.

But, we must also be concerned about the impact of agricultural decisions on the general public. For instance, if we were appraising the prospects of adopting the mechanical cotton harvester today, or any other of the many important technological developments of the past 30 years, we would certainly be forced to examine its impact on employment, community services, and other factors. Whether the questions involve mechanization or other commercial agriculture developments, we need to trace through the impacts of alternative development programs and be able to identify clearly just who gains and who loses.

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[2] Freddy K. Hines and Lynn M. Daft, *The Economic and Social Condition of Rural America in the 1970's: the Distribution of Federal Outlays Among U.S. Counties*, prepared by ERS for the U.S. Senate Committee on Government Operations, Government Printing Office, Washington, D.C., Dec. 1971.

Meeting Today's Research Needs

OUR intellectual and institutional capital for dealing with many of the problems I have cited is seriously lacking. We lack adequate theoretical constructs, methodologies, and organizational know-how to deal with many of the problems we will face in the next decade. The theoretical foundation for dealing with equity issues is especially weak. We have modern welfare economics, but this is not very satisfactory for solving many of the dynamic problems associated with who gains and who loses.

We also have serious organizational deficiencies. We have organized in terms of professions rather than in terms of problems. We have created artificial research boxes which look neat on organization tables but which fail to come to grips with real problems.

For example, the traditional research boxes in ERS in the form of divisions of Farm Production Economics and Marketing Economics often created stumbling blocks to dealing effectively with problems cutting across the entire beef industry, feed grain industry, and soybean industry.

Likewise, people with a need for public assistance are normally faced by a complex of problems rather than a single problem. Yet, we find a multitude of public programs, each dealing with a single problem. As we move toward a consideration of people and their problems, we must also move to a multiproblem approach in our research. Such team research is very difficult to organize within the constraints of our current research organizations.

Some Changes Made

THE Economic Research Service is aware of the problem and we are taking what I believe are significant steps. Recently we altered our research program away from the discipline-oriented research organization to one which is issue-oriented.

We have grouped three divisions—National Economic Analysis, Commodity Economics, and Foreign Demand and Competition—under a deputy administrator for food and fiber economics. This research area will focus on society-wide demands for sufficient supplies of agricultural commodities at reasonable prices.

Further, we have grouped three other divisions—Natural Resource Economics, Community and Human Resources, and Foreign Development—under a deputy administrator for resource and development economics. This area will focus on society-wide demand for equitable development of human and natural resources.

We also have eliminated the highly structured organizational lines in ERS; more specifically, the branches dealing with separate research areas. We will move toward a matrix type of organization. This means that we will bring several disciplines together on special issues. This helps streamline many of the administrative functions of the agency. But, more importantly, we hope this type of organization will equip us with the means to trace through all the consequences of a given development factor.

We will concern ourselves with the efficiency of our production and marketing system; but, we will also be concerned with what happens to people and their communities. Perhaps I can best illustrate our new approach by discussing our current research program in the flue-cured tobacco region.

Research on Flue-Cured Tobacco

OUR flue-cured tobacco research strategy is a team approach designed to understand the interactions between the commercial and human development aspects of the problem. The general study objectives relating to human resources development are to:

1. Determine the existing quantities and characteristics of human and capital resources employment in the production, marketing, and processing of flue-cured tobacco, and how these quantities and characteristics are likely to change during the next decade.

2. Develop a detailed profile of the human resources which are likely to be displaced and analyze the access these resources are likely to have to nonfarm employment opportunities in the region.

3. Evaluate programs and policies designed to assist the displaced human resources to obtain employment outside of agriculture, either within or outside the flue-cured tobacco area.

We now have 10 researchers addressing this issue and we expect this to increase to about 15 soon. We are using a matrix organization or coordinated team approach where various types of expertise are

brought to bear on a common problem. All research resources are under the direction of a project manager. Within 2 years, we expect to have the necessary understanding of this overall problem to advise policymakers on items ranging from on-farm mechanization to incentives for rural industrialization.

The expected mechanization of flue-cured tobacco harvesting and processing will almost certainly result in a series of interdependent adjustment problems in the flue-cured tobacco region. Moreover, reduced domestic or foreign demand for tobacco could further compound the seriousness of these problems.

The likely adjustment problems are both an industry and a regional problem. Mechanization of tobacco harvesting will result in substantial onfarm adjustments, and the adoption of new technologies in tobacco processing will bring about substantial adjustments in the tobacco processing plants. These adjustments will primarily substitute capital for labor.

Accompanying these problems will be regional adjustments associated with human resources. The initial adjustment involves a decrease in employment opportunities, and a need to expand employment opportunities in other industries in the region or prepare and assist the displaced workers to migrate to obtain employment in other regions.

The task of expanding nonfarm employment opportunities for the displaced workers is complex. Consideration must be given to the characteristics of the displaced workers and the characteristics of the manpower needs of industries which can profitably expand in the flue-cured region.

Difficult Questions

MANY industries have specialized needs which must be met before they can profitably locate in a given region. What are these special needs and what capabilities does the flue-cured tobacco region have for meeting these needs? If it is possible to expand nonfarm employment in a region, the industrial and occupational mix of the region will normally be altered. New public and private services must be added and in some cases old services substantially modified.

What do the displaced human resources do if there are no employment opportunities for them in the region? One alternative is to migrate to another region. This raises a number of equity-related questions. Should relocation assistance be provided? If so, to whom? Only displaced workers, or anyone in the region who wants to leave? Who are the gainers, and consequently who should be taxed to finance the relocation of the displaced?

Alternative means of livelihood, employment, or welfare for the displaced workers must be analyzed before programs and policies can be designed to deal effectively with the regional adjustment problems.

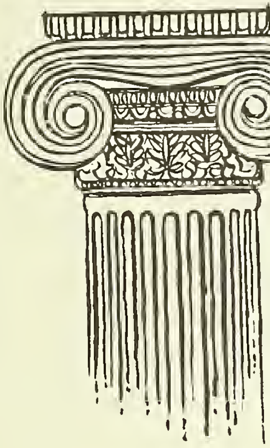
Perhaps the most important provision in the Rural Development Act of 1972 is the authority for government guaranteed loans, with no upper limit set, for rural industrialization. This gives us added impetus to pull together the research already done on rural industrialization and to propose new areas of needed research focusing on employment, income, population, housing, and community service goals for rural development.[3]

Summing Up

THE essence of our discussion can be summed up in terms of efficiency versus equity. In light of modern day America's concern over poverty, environment, and the general quality of life, it appears that equity is as important as efficiency, or possibly even more important. Frankly, our research program has emphasized efficiency—efficiency of commercial agricultural production and marketing. This concern must be continued but it must be tempered with an equal or greater concern over the side effects of efforts to achieve this efficiency.

There are trade-offs between efficiency and equity. But, unfortunately, in the past we have made these trade-offs in light of raw power—economic power, political power, the power naturally accruing to those privileged enough to have an effective voice. The poor and disadvantaged do not have this kind of power. Yet, we are publicly supported research organizations. We have the public responsibility to represent all segments of the society as we measure the trade-offs between efficiency and equity.

[3] Further discussion of the Act is contained in an ERS paper by Lynn M. Daft: *The Rural Development Act of 1972: What Is It?*, presented at the Conference on Manpower Planning for Jobs in Rural America, sponsored by Michigan State University and the U.S. Department of Labor, Austin, Texas, in December 1972.



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